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Responses of streamflow to vegetation and climate change in southwestern Australia

N. Liu[a,b,*], R.J. Harper[a,b,*], K.R.J. Smettem[a,c], B. Dell[a,b], S. Liu[b]

[a] School of Veterinary and Life Sciences, Murdoch University, South Street, Murdoch, WA 6150, Australia
[b] Chinese Academy of Forestry, Beijing 10091, China
[c] School of Civil, Environmental and Mining Engineering, The University of Western Australia, Crawley, WA 6009, Australia

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ABSTRACT

Southwestern Australia has experienced recent climate change, with an increase in air temperature of 0.6 °C and a reduction in mean annual precipitation of −15% since 1970. Along with the warming and drying trends, dramatic declines of streamflow have occurred across the region. However, both forest mortality and an increase in leaf area index have been observed in the southwestern forest, suggesting varied responses of vegetation to climate change. In this study, 30 catchments were analyzed using the Mann-Kendall trend test, Pettitt's change point test and the theoretical framework of the Budyko curve to study the rainfall-runoff relationship change, and effects of climate and land cover change on streamflow. A declining trend and relatively consistent change point (2000) of streamflow were found in most catchments, with 14 catchments showing significant declines ($p < 0.05$, −68.1% to −35.6%) over 1970–2000 and 2001–2015. Most of the catchments have been shifting towards a more water-limited climate condition since 2000. For the period 1970 to 2015, the dynamic of vegetation attributes (land cover/use change and growth of vegetation) dominated the decrease of streamflow in about half the study catchments. In general, a coequal role of climate and vegetation on the decline in streamflow was found in the study, suggesting the importance of vegetation management on future water management and production. Precipitation is predicted to decline in the future; therefore, some forest management intervention is required to maintain forest growth and water supply in the southwest of Australia.

1. Introduction

Temperate forests, which hold a great amount of terrestrial carbon, are quite sensitive to climate change and are particularly vulnerable to human land use; however, the net climate forcing and the response of temperate forests to climate change are still highly uncertain (Bonan, 2008). Forested catchments in Southwestern Australia (SWAU), which play a significant role in both water supply and carbon mitigation, are located in the temperate climate zone (Peel et al., 2007). SWAU has been experiencing profound climate change since 1950 because of the impacts of El Niño-Southern Oscillation (ENSO) and Indian Ocean sea surface temperature (Taschetto and England, 2009; Ummenhofer et al., 2009). Precipitation in SWAU declined significantly from 1950 to 1980, followed by a dramatic decrease in streamflow in 1975 (Bates et al., 2008). Although annual precipitation (P) of some catchments in SWAU has not shown any decreasing trends since 1989, streamflow and the runoff coefficient (the ratio of annual streamflow to annual P) demonstrated a significant decline with many streams shifting from perennial to ephemeral (Petrone et al., 2010, Zhang et al., 2016b). In addition, a marked decline in surface water available for storage was observed in dams around Perth (the capital city of Western Australia) (Water Corporation, 2019). The mean inflow to Perth dams decreased from an average of 173 GL between 1975 and 2000 to 92 GL between 2000 and 2009 and 46 GL from 2010 to 2017. It has been predicted that the drying trend in SWAU is likely to significantly affect various water balance components in the future (Ali et al., 2012; McFarlane et al., 2012). However, most vegetation in SWAU has shown an increase in leaf area index, even under dry conditions, for the past several decades (Donohue et al., 2009; Smettem et al., 2013). By analyzing the relationship between the vegetation index and water inputs (P and soil moisture (SM)), Liu et al. (2017) found that the change of vegetation indices, even during the driest period of 2002 to 2010, was not related to changes in water inputs for most of the forests in SWAU. Meanwhile, forest mortality was also reported in SWAU during the severe drought period of 2002 to 2010 (Harper et al. 2009; Brouwers et al., 2013; Evans et al., 2013). The opposite trends of vegetation and streamflow

* Corresponding authors at: School of Veterinary and Life Sciences, Murdoch University, South Street, Murdoch, WA 6150, Australia.
E-mail addresses: Ning.Liu@murdoch.edu.au (N. Liu), R.Harper@murdoch.edu.au (R.J. Harper).

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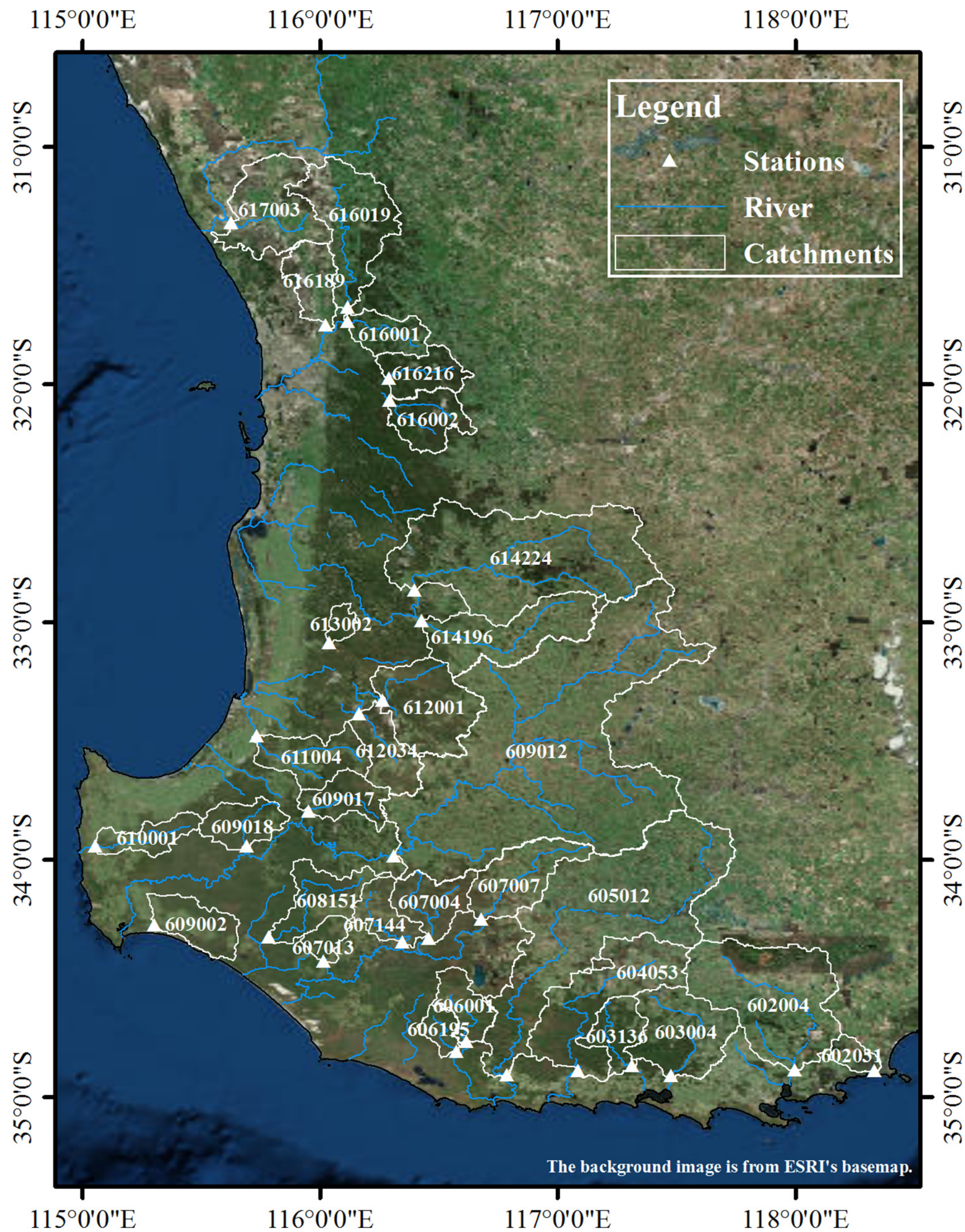

Fig. 1. Location of the 30 gauging stations and their related catchments in Southwestern Australia.

indicate some potential interactions between vegetation and streamflow under the changing climate. It is thus essential to comprehensively understand the reason for the streamflow decline.

The decline in precipitation has been considered as the main reason for the decrease in streamflow in SWAU since 1950, with 17% decline in P resulting in more than 50% reduction of streamflow (Petrone et al., 2010). It was predicted that the median projected decline (−8%) of P in the future would result in 24% decrease in streamflow (Silberstein et al., 2012). Apart from the effects of climate variables, Smettem et al. (2013) found that the greening trend of forests in the south of SWAU was another factor that led to the decrease of streamflow and groundwater level. Using fuzzy linear regression analysis in 145 global paired catchment experiments, Sahin and Hall (1996) concluded that a 10% reduction in eucalyptus forest cover could lead to an average 6 mm increase in streamflow in the first 5 years after the treatment. However, two recent paired catchment experiments in SWAU highlighted that even a 30% tree harvest and associated silvicultural treatments had no significant effect on streamflow (Kinal and Stoneman, 2011). Although there is no consistent conclusion of the effects of land cover/use change on streamflow, vegetation is still a critical factor affecting streamflow in SWAU. In the long-term, P, actual evapotranspiration (ET) and streamflow are the three main components of the water cycle in a catchment. Therefore, the dynamic of streamflow is dependent on the ratio of water output (ET) to input (P). This ratio is affected by both climate and vegetation and to fully understand the effects of climate and vegetation on streamflow, their relative contributions must be separated.

To separate the effects of climate from land cover and human activities on streamflow, four main approaches were summarized by Dey and Mishra (2017), namely: (1) experimentation; (2) hydrological modelling; (3) a conceptual approach and (4) an analytical approach. The experimental approach, such as paired catchments, is the most accurate method to separate the effects of climate and vegetation on streamflow (Brown et al., 2005). There are many paired catchment

experiments in SWAU (Bari and Ruprecht, 2003; Kinal and Stoneman, 2011; Ruprecht and Schofield, 1989, 1991a,b). Ruprecht (2018) reported that the paired catchment studies across SWAU forests have shown initial and longer-term impacts of forest disturbance. However, the impact across larger scales has not been clearly shown and the interaction of forest disturbance and a drying climate is difficult to distinguish (Ruprecht, 2018). In addition, the selection criteria for the "identical catchment" can be extremely hard to achieve and the experiment needs long-term observation data for the calibration. In addition, most of the existing paired catchments are based on small areas (Zhang et al., 2017), because it is difficult to conduct and monitor these experiments over large areas.

For the hydrological modelling approach, the selected hydrological model must be calibrated and validated firstly for a reference period, which can be quite time-consuming (Chang et al., 2016; Salazar et al., 2013; Tang et al., 2011). The main idea of using hydrological models is to fix either a climate or vegetation variable for each simulation. However, it is still difficult to address the interactive effects of climate and land cover on streamflow in reality, because the change of vegetation can be influenced by both climate and human activities. Conceptual and analytical approaches are based on mathematical analysis and an assumption that water balance in catchments remains steady for the long-term without significant change of vegetation and climate. Therefore, long-term observation of data is required to obtain the long-term water balance for the study catchment. These methods are applicable for large catchments, especially in catchments where it is too difficult for experimental methods to be applied. The sensitivity and decomposition methods, which were derived from Budyko's framework (Budyko, 1974), have been commonly used to separate the effects of climate and vegetation change on streamflow (Gao et al., 2016; Li et al., 2012, 2015; Zhao et al., 2014). Zhang et al. (2018) recently discussed the assumptions embedded in the Budyko framework and considered it to be useful as a first-order approximation for separating the contribution of climate change and land cover change on streamflow.

In this paper, catchments in SWAU, with long-term high-quality streamflow data since 1970 have been used to: (1) accurately identify the change points and trends of annual streamflow, climate variables and vegetation index; (2) study the relationships between streamflow, climate variables and vegetation at the catchment scale; and (3) quantify the relative contributions of climate change and land cover change to streamflow using Budyko's framework.

2. Material and methods

2.1. Study sites

There are around 700 gauging stations in Western Australia (www.bom.gov.au/waterdata/). Based on the availability of observed streamflow data from 1970 to 2015, 30 stations' upstream catchments were selected for this study (Fig. 1). These 30 stations have a long-period (> 30 years between 1970 and 2015) and high-quality (uncertainty < 20%) streamflow observations. Stations located downstream of water supply dams were excluded. The area of selected catchments ranges from 116 km^2 to 8729 km^2. There are 24 catchments that are mainly covered by eucalyptus open forest (forest coverage > 50%), while others were dominated by croplands in 2012 (Table S1). All the catchments are located in the Temperate Climate Zone and in water-limited areas (dryness index (DI) > 1) (Fig. 2), with mean annual P and air temperature (T) ranging from 503 to 1092 mm yr^{-1} and 15.3 to 18.6 °C, respectively. The evaporative index (EI, defined as ET/P) of these catchments is very high (> 0.8). Geographically, T increases from south to north, while P decreases inland from the coast. The mean normalized difference vegetation index (NDVI) of these catchments ranges from 0.55 (in non-forest dominant catchments) to 0.81 (forest catchments). More details of these catchments are in Table S1.

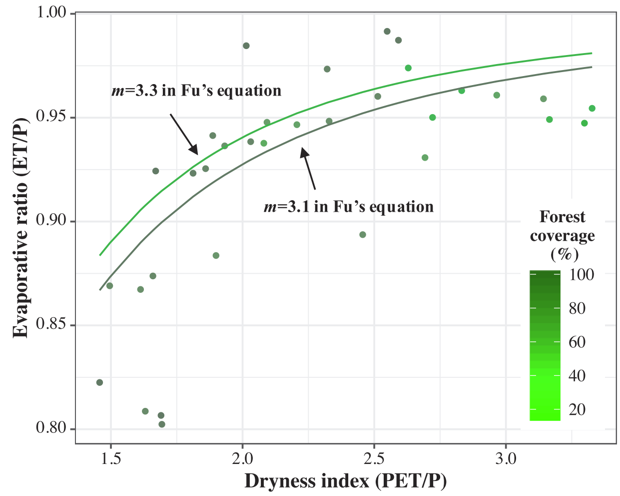

Fig. 2. Long-term (1970 to 2015) annual average dryness index (PET/P, the ratio of potential evapotranspiration to precipitation) against evaporative ratio (ET/P, the ratio of evapotranspiration to precipitation) for each catchment. The dark green and light green lines are the best fitted Budyko curves with Fu's equation using catchment parameter *m* for forest dominant and non-forest dominant catchments, respectively. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

2.2. Data

Monthly streamflows of 30 gauging stations in SWAU were obtained from the Department of Water, Western Australia. Groundwater data were obtained from the Australian Groundwater Explorer (www.bom.gov.au/water/groundwater/explorer/map.shtml). Bores with more than 20 years' continuous observations were used for the groundwater analysis. To reach the annual water balance for each year, the water year instead of the calendar year was used for calculating annual streamflow and all other variables in this study. The start and end months of the water year were calculated using the long-term monthly average of observed streamflow in each station. The water year begins with the month recording the minimum average monthly streamflow over the period of the data. The nominal year of the water year is the same as the calendar year when the start month is before July, otherwise, it is the following calendar year. Monthly climate data (T and P) were aggregated from 0.05° spatial resolution datasets of the Australian Water Availability Project (AWAP) (www.csiro.au/awap). This gridded climate dataset was derived using a topography-resolving analysis method with *in situ* observations for the period of 1970 to 2015 (Jones et al., 2009). Potential evapotranspiration (PET) was calculated using AWAP climate data with the Priestley-Taylor equation (Priestley and Taylor, 1972), which is recommended by Zhang et al. (2018). The NDVI, from the Global Inventory Monitoring and Modeling System (GIMMS)'s 1/12-degree data from 1982 to 2013, was used to analyze the dynamic of vegetation for each catchment. Forest coverage was calculated from tree cover data with the National Carbon Accounting System classification (Furby, 2002). The tree cover data, from 1972 to 2015, was derived from Landsat data and downloaded from http://wald.anu.edu.au/australias-environment/#Download. Forest is defined as tree cover > 30% (Specht et al., 1974). The study period for each catchment was dependent on the longest availability of streamflow data between 1970 and 2015, and the same period of other corresponding data (climate, NDVI and tree cover). These study periods are summarized in Table S1.

2.3. Statistical methods

The Mann-Kendall (MK) trend method (Burn and Elnur, 2002) with

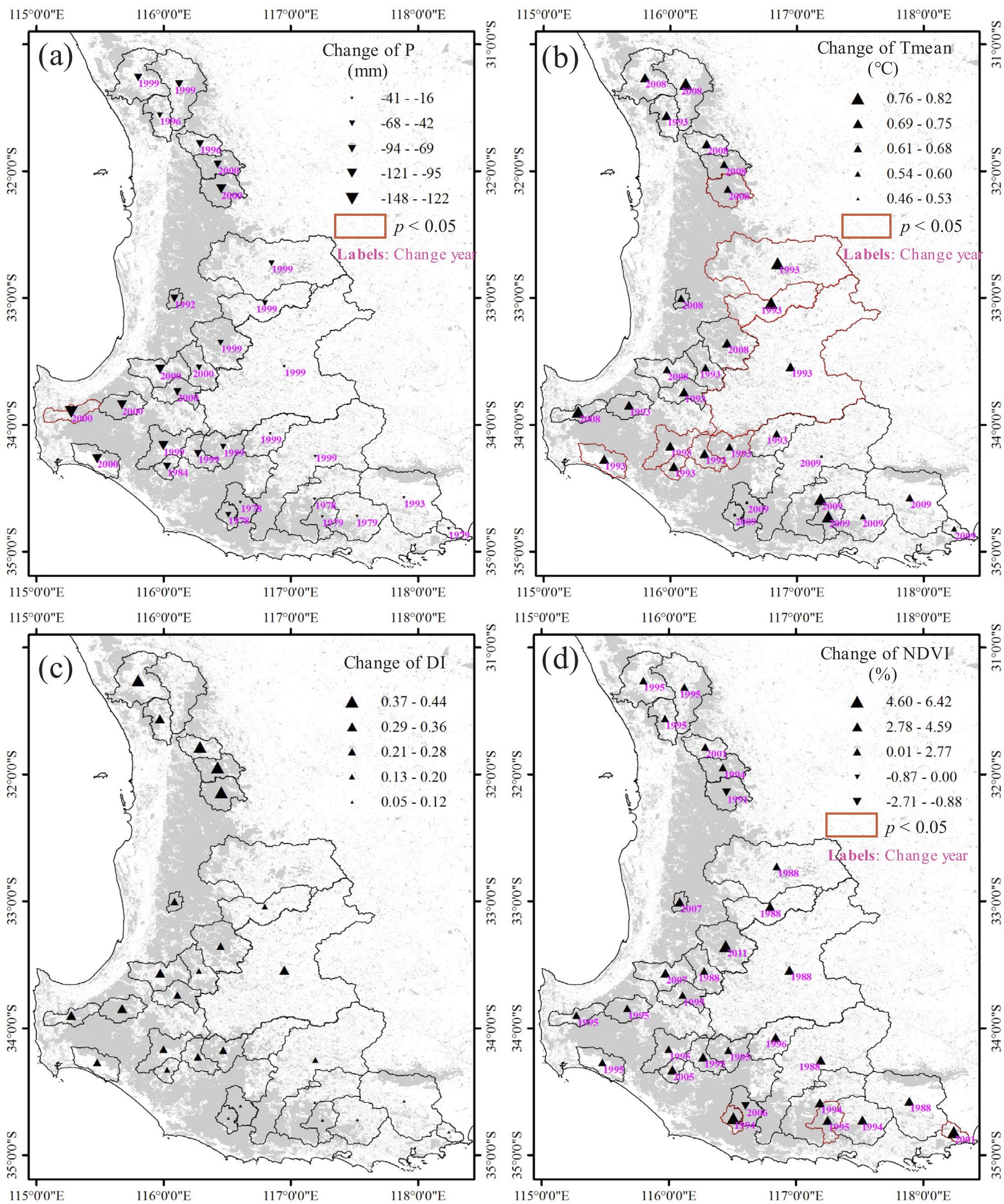

Fig. 3. Spatial changes of (a) annual precipitation (P), (b) annual mean temperature (Tmean), (c) annual dryness index (DI) and (d) annual mean normalized difference vegetation index (NDVI) between the pre-change period and the post-change period for each variable for each catchment. The red boundary means that a significant ($p < 0.05$) breakpoint was found in the catchment from 1970 to 2015, while labels were the detected change year. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

a trend-tree pre-whitening auto-correlation removing method (Yue et al., 2002) and Pettitt's change point test (Pettitt, 1979) were used for analyzing the time trend dynamics of all variables. For catchments where a significant breakpoint year ($p < 0.05$) of streamflow was detected by Pettitt's change point test method, the study period was split into two sub-periods (pre-change: before breakpoint −1, and post-change: after breakpoint). The runoff coefficient was defined as the ratio of the amount of runoff to the amount of annual P. In this study, it was calculated as the slope of the linear regression between annual P and streamflow. The slopes (runoff coefficient) of the linear regression models between annual P and streamflow for the pre-change period and post-change period were compared for difference using the "smatr" common slope test package in R 3.2.3. The relationships between streamflow, climate and vegetation variables were evaluated using Spearman's rank correlation in R 3.2.3 (Van de Wiel and Di Bucchianico, 2001).

2.4. Elasticity method

For catchments with a significant breakpoint ($p < 0.05$) of streamflow between 1970 to 2015, the Elasticity method was used to separate the contribution of climate and vegetation to streamflow. The change in annual streamflow from the pre-change period to the post-change period is defined as Δ_Q. For the long-term period, Budyko's

framework has been broadly used to reflect the reference condition of a catchment (Budyko, 1974). In this study, Fu's revised Budyko equation (Eq. (1)) (Fu, 1981) was used for analyzing the dynamics of the water balance in each catchment (Fig. 2). In Fu's equation, a parameter m is used to reflect the variation of water balance for different catchment characters.

$$EI = F(DI) = 1 + DI - (1 + DI^{m})^{(1/m)} \tag{1}$$

where, DI is the dryness index (potential evapotranspiration (PET)/precipitation (P)), EI is the evaporative index (evapotranspiration (ET)/precipitation (P)) and m is the catchment characteristic reflecting the soil properties, slope of the catchment, soil water content and vegetation cover, ranging from 1 to infinity. The value of 2.6 best reproduces the original Budyko curve (Wang et al., 2016). In this study, the best fit m is 3.2 for the selected 30 catchments (Fig. 2).

For a long-time period, change in soil water storage can be ignored in a catchment, so that water balance includes three components, P, ET and streamflow (Zhang et al., 2018). Assuming that P, PET and m are independent in Fu's equation (Eq. (1)), the change of streamflow (Δ_Q) is deduced from the variations of P (Δ_P), PET (Δ_{PET}), and m (Δ_m) (Eq. (2)). The contributions of these three components (P, PET and m) were calculated using the elasticity of streamflow to P (ε_P, Eq. (3)), to PET (ε_{PET}, Eq. (4)), and to the catchment parameter m (ε_m, Eq. (5)) (Sankarasubramanian et al., 2001; Gao et al., 2016).

$$\Delta_Q = \varepsilon_P \times Q/P \times \Delta_P + \varepsilon_{PET} \times Q/PET \times \Delta_{PET} + \varepsilon_m \times Q/m \times \Delta_m \tag{2}$$

$$\varepsilon_P = 1 + DI \times F'(DI)/(1 - F(DI)) \tag{3}$$

$$\varepsilon_{PET} = -DI \times F'(DI) \times (1 - F(DI)) \tag{4}$$

$$\varepsilon_m = -m \times F'(m)/(1 - F(DI)) \tag{5}$$

From Eq. (1), the first derivative of F with respect to DI ($F'(DI)$, Eq. (6)) and m ($F'(m)$, Eq. (7)) are followed (Gao et al., 2016):

$$F'(DI) = 1 - DI^{(m-1)} \times (1 + DI^{m})^{1/(m-1)} \tag{6}$$

$$F'(m) = (1 + DI^{m})^{1/m} \times \ln(1 + DI^{m})/m^2 - DI^{m} \times (1 + DI^{m})^{1/(m-1)} \times \ln(DI)/m \tag{7}$$

Generally, the catchment parameter (m) reflects the structure of vegetation, soil type, topography, and climate seasonality of the catchment (Donohue et al., 2010, 2012; Shao et al., 2012; Yang et al., 2009; Zhang et al., 2008; Zhao et al., 2010; Zhang et al., 2011).

3. Results

3.1. Dynamics of climate, vegetation and water for catchments

Since 1970, SWAU has experienced a significant warming trend, while precipitation slightly declined after 2000. Most of the catchments in SWAU shifted towards a more water-limited situation in the post-change period relative to the pre-change period (Fig. 3c). Even though there was a drying and warming condition in SWAU, a slight increase of NDVI was observed in most of the catchments since 1982. On the contrary, a significant reduction of both water yield and runoff coefficient was apparent in most of the catchments, especially those dominated by forest cover.

Annual mean temperature (Tmean) significantly increased in 9 catchments from 1970 to 2015 (Fig. 3b). A significant rise of Tmean generally occurred after 1993, which resulted in a substantial increase in PET in most of the catchments (Table 1). The rise in Tmean ranged from 0.46 to 0.82 °C between the pre-change and the post-change period of Tmean (Fig. 3b). The most considerable rise in Tmean (> 0.7 °C) was observed in the northern area of SWAU, while moderate warming (0.6 °C–0.7 °C) was found in the southern area of SWAU. The average annual maximum temperature (Tmax) increased (0.56–0.87 °C) more than the Tmean across all catchments in the southern area and had a lower standard error.

In contrast to temperature, only one catchment (No. 610001) showed a significant trend in P since 1970. A slight decrease (less than −15% (−150 mm)) of P was observed in most of the catchments (Fig. 3a). The breakpoint (not significant) of P for relatively dry catchments was generally in 1999 or 2000, while it was around 1978 for a few catchments in the southeast of the study area. The decline in P was higher in wet and forested catchments than in dry and non-forest catchments.

Most of the catchments (28 of 30) in SWAU showed an increase of NDVI since 1982, while NDVI decreased in two catchments in the northwest part of SWAU (Fig. 3d). The change of NDVI, ranged from −2.7% to 6.4%. Nine catchments showed a significant ($p < 0.05$) increasing trend of NDVI. Only 3 catchments showed a significant change point, including stations No. 602031 and 603136 where more than 5% reforestation was undertaken from 1995 to 2002 (Table 1). There has been widespread eucalypt reforestation in this region and this reforestation led to an increase of forest NDVI. A similar trend of NDVI was found between crop and forest for catchments without land cover change. For instance, at Station No. 603004, with 17.8% reforestation, the NDVI of the forest was observed to increase more than the crop between 1982 and 2013, while a similar trend of NDVI for forest and crop was found at Station No. 605012 (Fig. S1).

Fig. 4a and Table 1 demonstrated that 20 of 30 catchments experienced a significant decrease ($p < 0.05$ in Mann-Kendall trend test) in streamflow since 1970, while 14 of those 20 catchments had a significant breakpoint ($p < 0.05$ in Pettitt's change point test). The change in streamflow for all catchments ranged from −102 mm (−70.4%) to 14.3 mm (70%) (Fig. 4a and Table 1). For the 14 catchments with a significant breakpoint, 12 of them, (accounting for 50% of the forest catchments), were dominated by Eucalyptus forest, while only 2 of the 6 non-forested catchments demonstrated a significant breakpoint. Spatially, more catchments in the high rainfall area of SWAU, especially in the southwest area, showed greater declines in streamflow than in the inner dry region (Fig. 4a). Similar to the changepoint of P, streamflow of most of these catchments significantly changed in 1999 or 2000.

The runoff coefficient in all the catchments demonstrated a declining trend between the pre-change and the post-change period, with the change ranging from −0.27 to −0.01. Twenty-three of the 30 catchments, including 19 forest catchments, illustrated a significant breakpoint ($p < 0.05$) from 1970 to 2015. For catchments showing a significant decline in the runoff coefficient ($p < 0.05$ in "common slope" test), 10 of them showed a dramatic decrease in streamflow. The other 13 catchments experienced a shift in the relationship between rainfall and runoff even without a significant decline in streamflow during the study period, which suggests that there may be other factors affecting the rainfall-runoff relationship in these catchments. The decrease in runoff coefficient was more severe in the north than in the south.

3.2. Contribution of climate change and vegetation cover to the change in streamflow

There was a significant decline in streamflow in 14 catchments where a decreasing trend in P and an increasing trend in NDVI were observed (Section 3.1). As both a decline in P and vegetation change might affect water yield, the Elasticity method was used to separate the effects of climate change and vegetation on streamflow. In addition, correlations between streamflow and P and between streamflow and NDVI were analyzed using the Spearman's rank correlation method.

The elasticity of streamflow to climate and m were calculated based on Fu's equation in order to separate and quantify the contributions of vegetation change and climate variability to streamflow. The estimated m values in Fu's equation for the period 1970 to 2015 are shown in

Table 1
Trend and change point analysis for climate, vegetation and streamflow variables from 1970 to 2015.

Station	NDVI		Precipitation		Tmean		PET		Streamflow		Runoff coefficient	Forest cover change history
	Change (%)	Year	*Change* (%)	Year	*Change* (%)	Year	*Change* (%)	Year	*Change* (%)	Year	*Change (%)*	
602004	3.2	1988	−2.7	1993	3.6	2009[b]	2.2	2001	−54.9	2005	−72[c]	+5% from 1998 to 2002
602031	4.7	2001[ab]	−5.7	1979	3.5	2009[b]	2.6	2005	−23.6	1993	−37[c]	+18% from 1998 to 2002
603004	3.6	1994[b]	−4.5	1979	3.6	2009	2.0	2005	−48.7	1999[ab]	−45[c]	+17.8 from 1991 to 2005
603136	4.5	1995[ab]	−3.8	1979	3.7	2009	1.4	1993	−45.3	1993[ab]	−52[c]	+7.5 from 1998 to 2004
604053	3.3	1994[b]	−3.5	1978	3.8	2009	1.8	1993[ab]	−44.1	1999[b]	−46[c]	+9.2 from 1995 to 2002
605012	4.3	1988	−3.4	1999	3.9	2009[b]	2.1	1993[ab]	−48.3	2005	−51[c]	–
606001	−2.7	2006	−4.5	1978	4.2	2009	2.0	1993[ab]	−46.3	1999[b]	−51[c]	–
606195	4.8	1994[ab]	−5.2	1978	4.2	2009[b]	1.8	1993[ab]	−39.3	1981[ab]	−20	–
607004	2.8	1995	−7.3	1999	2.5	1993[ab]	2.4	1993[ab]	−67.8	2000[ab]	−68[c]	+6% from 1995 to 2002
607007	3.6	1996[b]	−4.5	1999	2.2	1993[b]	2.4	1993[ab]	69.0	1987	−5	+10% from 1995 to 2008
607013	3.0	2005	−8.0	1984	2.7	1993[ab]	2.5	1993[ab]	−41.7	2000[ab]	−28	–
607144	3.5	1995[b]	−9.2	1999[b]	2.7	1993[ab]	2.6	1993[ab]	−60.0	1999[ab]	−52[c]	+4.3% from 1995 to 2002
608151	2.1	1995	−10.3	1999[b]	2.7	1993[ab]	2.6	1993[ab]	−58.0	1999[ab]	−36[c]	–
609002	1.4	1995	−10.1	2000	2.1	1993[ab]	3.6	1993[ab]	−44.6	2000[ab]	−34[c]	+5% from 1998 to 2002
609012	3.0	1988	−7.4	1999	2.4	1993[ab]	2.6	1993[ab]	−31.7	2000	−41[c]	–
609017	2.5	1995	−9.4	2000	2.1	1993[b]	2.3	1993[ab]	−52.0	2000[b]	−55[c]	+5% from 1998 to 2002
609018	2.1	1995	−13.2	2000	2.0	1993[b]	2.7	1993[ab]	−54.0	2000[ab]	−40[c]	–
610001	2.5	1995[b]	−15.0	2000[ab]	3.5	2008[b]	3.5	1993[ab]	−54.1	2000[ab]	−36[c]	–
611004	3.7	2007[b]	−12.2	2000	3.6	2008[b]	2.5	1993[ab]	−38.1	2000	−41[c]	+4.3% from 1998 to 2004
612001	6.4	2011	−7.6	1999	3.3	2008	2.3	1993[ab]	−38.8	1996	−61[c]	+5.1% from 1992 to 2002
612034	1.7	1988	−9.2	2000	1.8	1993[b]	2.3	1993[ab]	−59.3	1996[b]	−60[c]	+6.5% from 1998 to 2004
613002	4.6	2007	−8.8	1992	3.8	2008[b]	2.2	1993[ab]	−52.2	2000[ab]	−53[c]	–
614196	3.4	1988	−11.0	1999	2.3	1993[ab]	2.8	1993[ab]	30.1	1990	−39	–
614224	2.4	1988	−11.5	1999	2.6	1993[ab]	2.7	1993[ab]	−45.7	2000	−57[c]	−3.6% from 1998 to 2002
616001	1.5	2001	−10.3	1996	4.4	2008[b]	2.7	1993[ab]	−43.2	2000[ab]	−24	–
616002	−0.9	1991	−13.7	2000	4.5	2008[b]	2.2	1993[ab]	−70.4	2000[b]	−71[c]	–
616019	2.0	1995	−11.8	1999	3.9	2008[b]	3.0	1993[ab]	−54.8	2005	−49[c]	–
616189	1.8	1995	−9.1	1996	2.0	1993[b]	2.9	1993[ab]	−59.1	2000[ab]	−40[c]	−10% from 2002 to 2007
616216	1.5	1994	−13.6	2000	4.4	2008[b]	2.4	1993[ab]	−69.0	2000[b]	−73[c]	–
617003	2.4	1995	−11.2	1999[b]	3.8	2008[b]	3.0	1993[ab]	−58.5	1999[ab]	−43[c]	−10% from 2002 to 2007

Note: "[a]" means $p < 0.05$ for Pettitt's change point test; "[b]" means $p < 0.05$ for Mann-Kendall trend analysis; "[c]" means $p < 0.05$ for runoff coefficient change analysis and "–" mean almost no change in the forest coverage. NDVI is normalized difference vegetation index for the period of 1982 to 2013, Tmean is mean temperature and PET is potential evapotranspiration.

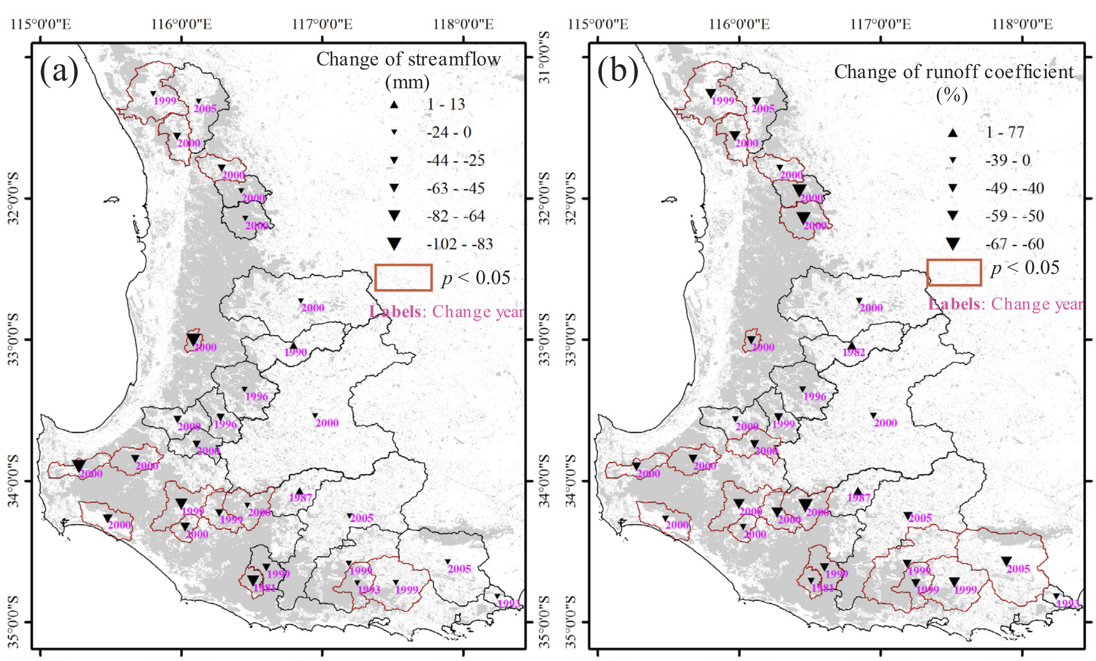

Fig. 4. Change of (a) streamflow and (b) runoff coefficient from the pre-change period to the post-change period. Red boundary means that a significant ($p < 0.05$) breakpoint was found in the catchment from 1970 to 2015. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Table 2
Change of each variable from the pre-change period to the post-change period of streamflow.

Station	Year	Pre-change			Post-change			Change				Contribution		
		P (mm)	PET (mm)	Q (mm)	P (mm)	PET (mm)	Q (mm)	P (%, mm)	PET (%, mm)	Q (%, mm)	ET (%, mm)	P (%)	PET (%)	Vegetation (%)
603004	1999	715	1488	44.6	698	1510	22.5	−2.5(−17)	1.5(22)	−49.6(−22)	0.8(5.1)	15.3	6.1	78.6
603136	1993	798	1507	46.8	784	1525	26.6	−1.8(−14)	1.2(18)	−43.3(−20)	0.8(6.2)	14.0	6.5	**79.5**
606195	1981	1028	1498	182.5	1002	1506	117.4	−2.6(−26)	0.5(8)	−35.6(65)	4.6(39.1)	17.7	2.2	**80.1**
607004	2000	679	1575	18	630	1608	5.8	−7.2(−49)	2.0(33)	−68.1(−12.2)	−5.6(−36.8)	38.7	8.0	**53.3**
607013	2000	1023	1530	134	941	1566	78.0	−8.0(−82)	2.3(36)	−41.8(−56)	−2.9(−26.0)	**53.8**	10.0	36.2
607144	1999	795	1537	50.6	732	1571	22.6	−8.0(−63)	2.2(34)	−55.3(−28)	−4.7(−35.0)	46.1	8.9	45.1
608151	1999	942	1564	118.9	848	1600	57.4	−10.0(−94)	2.3(36)	−51.8(−62)	−3.9(−32.5)	**52.0**	7.6	40.4
609002	2000	1028	1657	136.4	924	1711	75.8	−10.1(−104)	3.3(54)	−44.4(−61)	−4.9(−43.4)	**60.7**	12.2	27.1
609018	2000	910	1649	69.9	792	1685	32.2	−13.0(−118)	2.1(36)	−53.9(−38)	−9.6(−80.3)	**75.1**	8.4	16.5
610001	2000	985	1606	188.4	840	1653	86.6	−14.7(−145)	2.9(47)	−54.0(−101.8)	−5.4(−43.2)	**60.8**	6.7	32.5
613002	2000	1013	1712	195.8	915	1736	93.7	−9.7(−98)	1.4(24)	−52.1(−102)	−8.4(−55.3)	40.8	3.2	**56.1**
616001	2000	738	1812	78.4	649	1849	44.7	−12.0(−89)	2.1(37)	−42.9(−34)	−8.7(−52.8)	**66.6**	6.7	26.7
616189	2000	695	1871	48.1	631	1911	19.5	−9.1(−64)	2.1(40)	−59.4(−28.6)	0.8(6.2)	40.4	5.9	**53.8**
617003	1999	633	1876	24.8	566	1925	10.6	−10.5(−67)	2.6(49)	−57.1(−14.2)	4.6(39.1)	**54.2**	8.8	37.1

Note: P is precipitation, PET is potential evapotranspiration, *m* is catchment character, DI is dryness index, EI is evaporation index and Deviation (*d*) is defined as the ratio of EI to DI. Contributions, larger than 50%, are in **Bold** font.

Table S1. For the 30 catchments, *m* ranged from 2.4 to 4.5 with a mean of 3.2, with no significant spatial pattern in SWAU. From the pre-change to the post-change period of streamflow, the change in *m* was much larger (13 ± 5%) than the change in P (−8.9 ± 3.7%) and PET (1.9 ± 0.7%). Both *m* and PET increased in most of the catchments in SWAU, while P decreased in SWAU. In general, the streamflow in SWAU showed the highest positive sensitivity to the change of P, while negative sensitivity was found to changes in PET and *m*. A 10% increase in P may increase streamflow by an average of 30%, while a 10% increase in PET may decrease streamflow by 20%. A 10% increase in *m* may decrease streamflow by 34%. Moreover, the streamflow in 7 of the 14 catchments where significant change points were detected was more sensitive to vegetation change than climate variability. As shown in Table S2, the mean values of ε_P, ε_{PET} and ε_m in the forested catchments were 2.9, −1.9 and −3.2, respectively, while those in the non-forested catchments were 2.8, −2.1 and −3.8, respectively.

The contributions of P, PET and *m* to streamflow change were calculated based on Eq. (2). The results showed that average contributions of P, PET and *m* to the total reduction in streamflow were 45.4, 7.2 and 47.4%, respectively. About half of catchments showed a higher contribution of P than *m* and PET (Table 2). Overall, vegetation and climate made coequal contributions to streamflow. Reforestation resulted in an increase of ET, while a drying climate led to a decline of ET (Table 2). The contributions of the vegetation were generally higher in catchments with considerable land cover change than in other catchments. Fig. 5 shows the dynamic of streamflow in two catchments, as examples, one of which was dominated by climate change (Station No. 609018) and the other dominated by land cover change (Station No. 603004). The forested catchment 609018 (94% forest) had not experienced a change of land cover, or a significant change in the NDVI of the forest (Table 2), however a significant decline of streamflow (−40%, $p < 0.05$) was observed in 2000 when a decrease in P (−13.18%) were observed (Table 2 and Fig. 5). This negative change in P suggested that the decline in streamflow was mainly a result of the drying climate, which is also shown in the elasticity result with the contribution of P, PET and *m* to streamflow of 75.1%, 8.4% and 16.5%, respectively (Table 2). For the other catchment 603004, which had a slight decline in P (−4.5%) since 1979, reforestation commenced in 1991 and plantations represented 17% of the area by 2005, hence there was a significant increasing trend of NDVI from 1995 (Table 1). The contribution of P, PET and *m* to streamflow in catchment 603004 were 15.3%, 6.1% and 78.6%, respectively (Table 2), which indicated that the decline in streamflow is because of the land cover change.

In addition to the Elasticity method, Spearman's rank correlation was used to examine the relationship between annual P, streamflow and NDVI from 1970 to 2015. The results showed that streamflow and P demonstrated significant ($p < 0.05$) correlations for all of the 30 catchments (Table S2), with the correlation coefficient (*rho*) of Spearman's tests ranging from 0.62 to 0.89. Only Stevens Farm Catchment (Station No. 6002004) showed a significant relationship between streamflow and NDVI (*rho* = 0.36) and between P and NDVI.

4. Discussion

4.1. Relationships between streamflow, climate and vegetation changes

Overall, no significant change in P was observed in SWAU since 1970; however, for most of the 30 catchments, Tmean and PET increased considerably from 2008 and 1993, respectively. Meanwhile, most of the catchments showed significant declines in annual streamflow with corresponding breakpoints in 2000. Although there was no significant downward trend in P since 1970, there was about a 10% decline in P in many of these catchments, suggesting that P may be one of the factors that resulted in the reduction in streamflow. Similarly, a strong relationship between P and streamflow from Spearman's rank correlation test was found in SWAU (Table S2), indicating that the dynamic of streamflow was strongly related to a change in P. Similar results were found using the Elasticity method, which showed that streamflow declined in a half of the catchments because of the decline in P. Although streamflow was strongly related to P in most of the catchments, vegetation also played a critical role in the significant decline in streamflow for the study period, especially in catchments with substantial land cover change. For instance, there are two similar catchments - Dingo Road (Station No. 613002) and O'Neil Road (Station No. 614037), with forest coverage of around 100%. Although declines in P (−10% decline) were observed in these two catchments, the Dingo Road catchment experienced an increase of NDVI (11.4%) but significant decline in streamflow (−52%, $p < 0.05$), whereas the O'Neil Road catchment had the opposite trend of NDVI (−1.0%) and no significant decline in streamflow (−51.0%, $p > 0.05$). Contributions of climate and vegetation to streamflow in Dingo Road were 40% and 56%, respectively. Zhang et al. (2011) concluded that the contribution of vegetation and climate on streamflow change was 93% and 13%, respectively, in the Upper Denmark Catchment (an upstream catchment of Station No. 601136) during the period of 1989–2008, while the contribution in this study in Station No. 603136 was 79.5% for

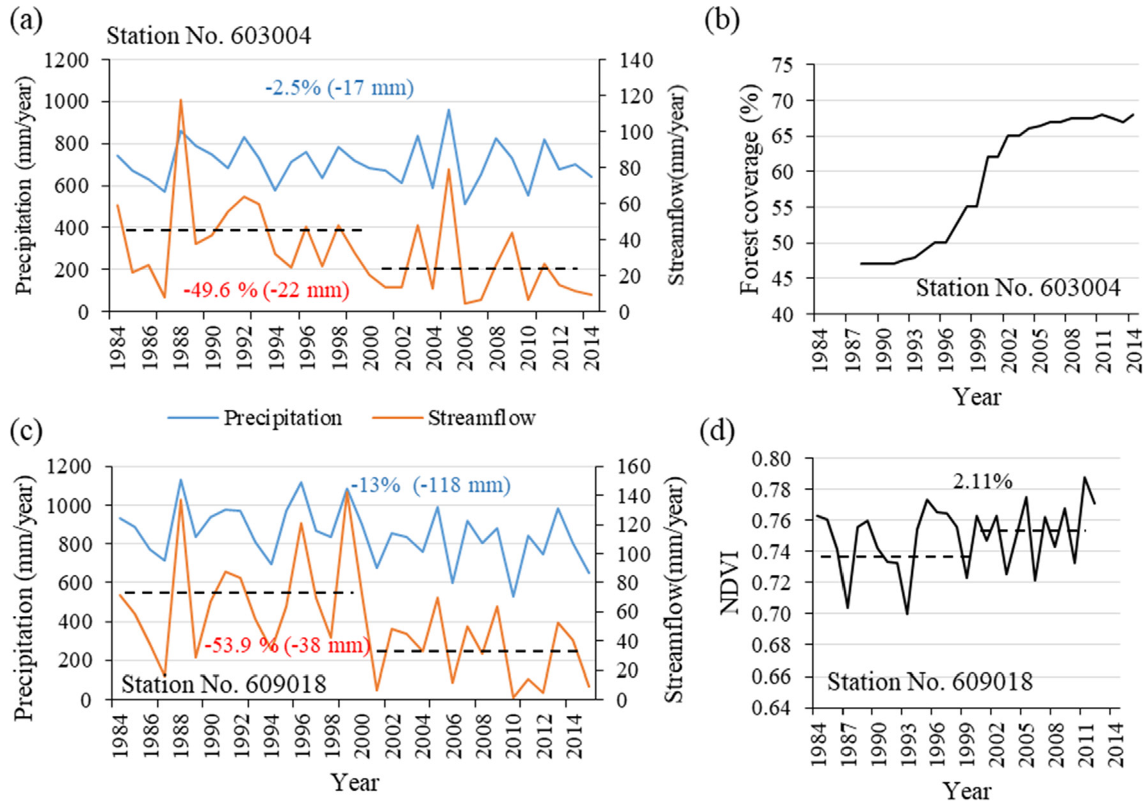

Fig. 5. Change of water and catchment characteristics at Hay River (Station No. 603004) (a and b) and St John Brook (Station No. 609018) (c and d) for the study period.

vegetation and 14% for P and 6.5% for PET. Apart from the land cover change, forest biomass growth could be another reason for the increase of the evaporative ratio (Renner et al., 2014; Jaramillo et al., 2018). For instance, at Station No. 606195, NDVI significantly increased since 1982, which contributed to an 80% decline in streamflow. Although there is still some uncertainty surrounding the "fertilization effect" of rising CO_2 on vegetation (Fatichi et al., 2016; Gimeno et al., 2018), the growth of the forest might be due to the positive response of photosynthesis to increasing atmospheric CO_2 levels (Friend et al., 2014). In contrast, rising CO_2 could result in the decline in ET by decreasing stomatal conductance. Using four global vegetation dynamic models, Huang et al. (2015) found that the rising CO_2 would result in an increase in gross primary production (GPP) and ET ignoring the effects of climate change, indicating that the CO_2 might contribute to the increase in evaporative ratio in southwestern Australia. In addition to streamflow, Trancoso et al. (2017) reported that increasing atmospheric CO_2 and its associated vegetation feedbacks are reducing base flow in addition to other climatic impacts in eastern Australia.

Climate and vegetation have been reported as the most critical factors affecting catchment water balance (Wei et al., 2018). In this study, the average contribution of climate and vegetation is almost equal, which is consistent with the global analysis using 168 large catchments (Li et al., 2017). Climate and vegetation interactively affect groundwater levels, which may further affect the water supply to vegetation and hence, vegetation health in SWAU. The combination of a declining P and an increasing NDVI resulted in a decrease in groundwater discharge (Fig. S2) and a disconnection between groundwater and streamflow (Kinal and Stoneman, 2012). Dawes et al. (2012) reported that recharge rates have increased in deforested areas but decreased in forested catchments where P has experienced a major decline. The decline of groundwater levels might explain the reason why forested catchments have experienced a more dramatic decline in streamflow than non-forested catchments in SWAU. The decline of groundwater has also been suggested as the reason for forest mortality in the northern Jarrah forest (Brouwers et al., 2013; Evans et al., 2013), however, this may be exacerbated by limited soil depth and hence limited soil water storage in some of these catchments (Harper et al., 2009).

4.2. Possible drivers of change in the catchment characteristic m

The catchment parameter reflects the allocation of water input to streamflow and ET, leading to the different profiles of the Budyko curves (Fig. 2). P has been reported as a crucial factor affecting catchment properties (Jiang et al., 2015), especially in arid areas (Padrón et al., 2017); therefore, climate change may affect streamflow not only by changing the hydrological input (P) and output (ET) but also by altering the catchment characteristics as represented by the parameter m. For example, climate change may affect m by changing the vegetation structure as well as soil water storage. Tang and Wang (2017) tested the performance of four parameters to reflect the long-term water balance of a catchment. They found that watershed properties have positive correlations with rainfall variability (the average time interval between rainfall events) and soil properties (permanent wilting point) and negative correlations with topography (slope) and vegetation index. Using different sources of evapotranspiration data, Condon and Maxwell (2017) analyzed the impacts of storage changes on the parameter m in catchments spanning the majority of the continental US. They reported that positive groundwater contributions (positive fluxes from the surface to the subsurface) will increase m, with the sensitivity of m to storage changes varying non-linearly with both the aridity of the watershed and the evapotranspiration fraction. Groundwater, derived from the annual mean groundwater level between pre-change and post-change of streamflow during the study period, has experienced a considerable drop (negative contribution) in most of bores (Fig. 2S) due to the drying trend (Kinal and Stoneman,

2012), which suggested that there is a potential decline of *m* between pre-change and post-change period for those catchments. Therefore, the Elasticity method might overestimate the contribution of climate change on streamflow due to the negative contribution of groundwater change. Meanwhile, Bari and Smettem (2006) found a nearly 15 m rise in groundwater over 20 years following clearing of 53% of forest in Lemon catchment in Western Australia, which could offset the impact of the drying trend on groundwater.

Furthermore, relationships between *m* and climate variables (P, Tmean), vegetation (NDVI and Tree coverage) and topography (catchment size and mean catchment slope) were analyzed using Spearman's method for the studied catchments, and the results showed that *m* was only significantly ($rho = 0.35$, $p < 0.05$) related to tree coverage. Similarly, Donohue et al. (2010), using 200 catchments in Australia, found that the fraction of photosynthetically active radiation (fPAR) can reflect 70% variation of *m*. Using data from 26 major global river basins, Li et al. (2013) confirmed that *m* is linearly correlated with the long-term average annual vegetation coverage. Furthermore, Zhang et al. (2016a) revealed that fPAR can explain 60% of the variation in *m* for catchments across the Loess Plateau in China. Apart from the effect of fPAR on streamflow, Donohue et al. (2012) also showed that the depth of plant roots and plant-available soil water holding capacity can influence streamflow estimated from the Budyko model. Smettem and Callow (2014) further validated the performance of the model by including root and storm depth in Budyko's framework using 11 catchments in the south of SWAU.

Apart from those natural impacts, several human activities, such as cropland expansion, irrigation, and the construction of reservoirs could also lead to the change of streamflow (Wang and Hejazi, 2011). Most of the cropland in this study are dryland (non-irrigated) agriculture, with < 5% irrigated area in each catchment (Siebert et al., 2013). Irrigation water is mainly sourced from former water supply dams (not included in the study area) in the forest area and used outside the study region. On farm use of groundwater for irrigation is highly limited due to the high salinity levels (Clarke et al., 2002). Assuming that for the long-term period there is no change in soil type and geological characters and, ignoring those potential non-vegetation effects on *m*, the change in *m* mainly results from changes in vegetation. Therefore, the contribution of *m* to streamflow in the study catchments can be used to reflect the contribution of the dynamics of vegetation to streamflow.

5. Conclusions

This study identified the relationship between climate, vegetation and streamflow in SWAU for the period 1970 to 2015. The results indicate that both forested and non-forested catchments in SWAU have been undergoing drying conditions, with a decline in both surface water yield and groundwater levels. Furthermore, the results indicated that climate change and dynamics of vegetation, reflected in NDVI change and land cover change, contributed, on average, equally to the decline in streamflow. Our findings also highlight the vulnerability of streamflow in water limited environments to the combined influence of changing climate drivers and vegetation. As precipitation is predicted to further decline in the future, thoughtful consideration needs to be given to forest management to ensure the long-term maintenance of stream flows in this region.

Declaration of interest

None.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jhydrol.2019.03.005.

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